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PREFACE

This research was sponsored by AMP, Incorporated under the technical guidance of Mr. Charles R. Heath. The authors are particularly indebted to Mr. Heath for his painstaking attention to the design and purpose of this research, his efforts in procuring the software and hardware needed for the research, and his understanding of the technical difficulties involved in combining the various technologies required for completion of the project.

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INTRODUCTION

Computers and their corresponding interactive display and control devices were, at one time, available to a limited user population. With technological advancement, human-computer interaction has become accessible to a larger user population through the use of electronic displays and their associated input devices.

Touch Entry

In the early 1960s, the use of the display plane as an interactive surface was realized by E. A. Johnson at the Royal Radar Establishment in Hurn, U.K. (Orr and Hopkin, 1968). The input device subsequently designed and developed is referred to here as a touch entry device (TED). TEDs take advantage of the natural mode of pointing, as do light or sonic pens, without the need to use a stylus or additional cumbersome wirings. Many technological approaches to touch entry have been developed and implemented since its first inception. However, the operational characteristics of each TED must be considered in the application of these devices to disparate types of tasks. The following is a discription of seven operationally different TEDs.

Touch Entry Devices

Touch Wire TED. The first TED, designed and developed

by E. A. Johnson (Orr and Hopkin, 1968), is known as a "Touch Wire" TED or the "Johnson Switch". The Johnson Switch consists of a transparent overlay made of a polyester-type material or of glass. Exposed wires are raised above the surface of this overlay. These wire switches are spaced along four rows with six switch sites per row. Command functions are displayed directly above the wire switches. Initiation of a response to an input or command selection is achieved by the touch of a finger.

When an operator's finger contacts a wire switch, the operator's body produces a capacitance and resistance to earth (ground), which unbalances an inductance capacitance bridge (Hopkin, 1971; Johnson, 1967; Orr and Hopkin, 1968), thus completing a circuit. The signal path to the computer is similar to that of a keyboard.

Cross-Wire TED. The Johnson switch has evolved into a wire matrix device. Horizontal and vertical wires are respectively affixed to opposing sheets of a transparent polyester-type material. The intersection of wires creates static switch sites resembling crosshairs. In operation, a small current is applied to either the horizontal or vertical wires. The opposing wires provide a return path when sufficient pressure is applied to the overlay, causing wire contact. A resulting X,Y position is then encoded.

Capacitive TED. As with the Johnson switch, this touch entry device also exploits the body's capacitance, but in a

different manner. A conductive film is vacuum deposited or fired on as a continuous coat segmented pattern on the surface of a plate glass overlay. In operation, a constant voltage is applied to the surface of the overlay. When touched by an operator, a coupling of panel current and body capacitance occurs. A resulting electrical signal is produced when the new panel current is compared to a square-wave reference current (Ritchie and Turner, 1975).

Conductive Film TED. Typically, one layer of this TED is composed of either glass or a thick (.030 to .040 in.) polyester-type material upon which a resistive medium (usually gold or indium tin oxide) is vacuum deposited. A more flexible layer, again composed of a polyester-type material (.003 to .005 in.), overlays the first and is vacuum deposited with a conductive material. The opposing layers are commonly separated by a perforated dielectric. This TED is essentially a large analog membrane type switch.

In operation, a voltage is alternately applied to the X and Y axes of the resistive layer (Sierracin, 1981; Thompson, 1980). When an operator's finger forces the two layers together, two voltage levels and a resultant current flow are created. These potential gradients are then encoded into X,Y coordinates by electronically sampling the opposing (X and Y) analog voltage levels. The resulting signal undergoes an analog-to-digital conversion at the interfacing electronics (Thompson, 1980).

Acoustic Ranging TED. The working principle of this TED is similar to that of sonar. Ultrasonic waveforms, emitted from either ceramic or piezoelectric transducing crystals, traverse an overlay (plate glass) or the surface of the display screen along both X and Y axes. Two configurations are common. In the first, transducing crystals are affixed to a glass plate overlay, one row across the top of the overlay and one column along the left side (de Bruyne, 1980; Fajans, 1977; TSD Products, 1981). When the transmitted waveforms contact an object in their path, they are reflected back to their source. The time between transmission of the waveform and reception of the reflected waveform is calculated for both X and Y axes and is encoded as an X,Y position.

The second configuration employs opposing transmitting and receiving crystal pairs mounted directly on the outer edges of the display surface. When the X and Y reference waveforms are interrupted by an operator's finger, an X,Y position is encoded in the same manner as previously described (Fryberger and Johnson, 1971; Hlady, 1969). Further, by alternately pulsing the column and row crystals, an operator's finger can be tracked with respect to fixed reference axes (de Bruyne, 1980).

Infrared (IR) TED. This TED technology was first developed at the University of Illinois in conjunction with the PLATO (Program Logic for Automated Teaching Operations) system (Ptauth and Priest, 1981). Infrared beam

transmitters and photocell receptor pairs are combined to form the sensing mechanism. The infrared transmitters and photocell receptors are commonly affixed to a peripheral assemblage and arranged in linear arrays around the edge of the display screen, forming a matrix. Therefore, no overlay is associated with this device and no loss in display luminance or image quality results. In operation, IR beams traverse the display screen along both X and Y axes. When an operator's finger "breaks" an IR beam intersection, a resulting X,Y position is encoded.

There are several areas of concern in the application of this TED which were noted by Pfauth and Priest (1981). The first is that as an infrared beam travels toward its corresponding photoreceptor, the beam diverges covering more than one photoreceptor. Although lenses could be used to collimate the beams and control their divergence, such a control would introduce an interdiode spacing constraint, thus limiting the switch site resolution of this TED. By pulsing the IR beam emmitters, the diodes can be placed closer together and a greater switch site resolution realized. Further, by pulsing the diodes, only one IR pair (emitter and receptor) is activated at any point in time. Therefore, the intensity of the IR output is increased, allowing the diode pairs to be separated by greater distances (distance as measured across the display surface). Beairstro, Hastbaka, and Cowley (1978) reported an effective separation of diode pairs of up to 20 inches.

The effects of changing and different ambient illumination also have been a concern in the application of this TED. By sampling the ambient illumination, a threshold is established and is stored in memory. By referring to this stored light threshold, the illumination necessary to be sensed is transmitted, providing a correction for environmental light "noise" (Beairstro et al., 1978; Bird, 1977).

A third concern in the application of this TED technology is that of parallax, particularly in CRT applications. Physical parallax is caused by the increasing distance between the curved portion of the CRT screen and the fact that IR beams travel only in straight paths. Beairsto et al. (1978) have attempted to resolve this parallax problem by using a pair of transmitters and a corresponding pair of photocell receptors on each of the four sides (top, bottom, left, and right) of the CRT screen. By employing such a design, the IR beams are brought closer to the surface of the display screen, essentially dividing the active area of the TED-display system into quadrants. However, these authors admit that the problem of parallax still exists.

Another approach (Carroll Manufacturing, 1980) is to place IR emitters and photocell receptors in a pattern following the curvature of the CRT screen. Although attempts have been made to reduce parallax, the concern for parallax in the application of this TED remains.

Pressure Sensitive TED. As discussed by Herot (1978) and Negroponte, Herot, and Weinzapfel (1978), this membrane-like overlay incorporates four pairs of strain gauges as the sensing mechanism. The strain gauges are mounted in pairs between the display screen and the overlay, one on each of the four sides (top, bottom, left, and right). One strain gauge of each pair measures the force perpendicular to the overlay, while the others measure shear parallel to the overlay.

The output voltages of the strain gauges are electronically filtered and correspond to six X, Y, and Z force and torque values. These outputs are then encoded into X,Y coordinates and codes for direction and acceleration for cursor movement (Herot, 1978; Negroponte *et al.*, 1978).

METHOD

This research was carried out in four phases. In Phase I, a photometric evaluation designed to quantify the physical display quality for 10 unique CRT-TED systems was conducted. Phase II consisted of a series of experiments designed to assess operator performance using the same 10 CRT-TED systems in three generic tasks. Subjective assessments of TED utility were collected during Phase III. In Phase IV, correlational analyses were conducted in an attempt to relate CRT-TED system optical quality, quantified in Phase I, to the human performance and subjective assessment data, collected in Phases II and III.

Phase I

The CRTs were optimized to their best possible display conditions by manipulating the parameters directly affecting the image quality of displayed information such as the luminance, contrast, and focus. The modulation of each CRT and CRT-TED system was measured at both high and low spatial frequencies. Display system noise levels, characterized by luminance variations and raster modulation, were measured and quantified.

The purpose of measuring the luminance capabilities of each CRT and CRT-TED system is to obtain a quantitative index of display resolution within the limits of the passband of each CRT under the appropriate conditions. To obtain an index of display resolution, an image (generally a

grating pattern) can be presented at different spatial frequencies and the contrast (modulation) measured at each frequency. Alternatively, a single pixel wide line may be presented and scanned by using the line spread function (LSF) analysis technique. The LSF, as used in this phase, is defined by the luminance profile of a one-pixel-wide image measured photometrically on the display surface.

Apparatus. The five TEDs evaluated were (1) an acoustic ranging (AR) device (TSD Products, Incorporated), (2) a capacitive (CAP) device (Interaction Systems, Incorporated), (3) a conductive film (CF) device (Sierracin/Intrex Corporation), (4) a cross-wire (CW) device (AMP, Incorporated), and (5) an infrared (IR) device (Carroll Manufacturing Company).

Each TED was mounted separately on two CRT displays. These displays were (1) an NEC chassis with a 31-cm diagonal P-31 phosphor tube and (2) an NEC chassis with a 31-cm diagonal P-4 phosphor Clinton tube. An additional CRT (a Conrac 31-cm diagonal P-4 phosphor tube) was originally included in this research. However, due to horizontal deflection problems this CRT was excluded from the photometric evaluation and subsequent human performance experiments. The 10 CRT-TED display systems were driven by an APPLE II PLUS 48K microcomputer with high resolution graphics.

The photometric equipment used in this phase consisted of a scanning eyepiece (Gamma Scientific, Model 700-10)

fitted with a 0.025 x 2.500 mm slit aperture. The eyepiece was configured with a microscope having a 2.4X magnification objective. The scanning optics were connected to a photomultiplier tube by means of a fiber optics cable. The photometric system employed in this phase is the Gamma Model 2400.

The photometric system was calibrated to an NBS-traceable light standard designed and constructed in the Human Factors Laboratory. The scanning eyepiece assembly was mounted on an Aerotech 260D x-y positioner. The x-y positioner and the photometric system were controlled by a PDP 11/55 - LPS 11 computer system. The luminance of the display, sampled at discrete points, enters the light microscope and passes down the fiber optic cable to the photomultiplier (PM) tube. In the PM tube the light energy is converted to a proportional current and the resultant signal is sent to the photometer. The luminance is then read by the photometer and its value output as an analog voltage. This voltage is then conditioned at the DC amplifier and sent to the PDF 11/55 computer, via the LPS, and stored on disk for later analysis. An overview of the data collection and data reduction procedures is shown schematically in Figure 1.

Procedure. Display resolution measurements used the LSF method to determine the modulation transfer function of each CRT-TED system. LSF scans were made in several

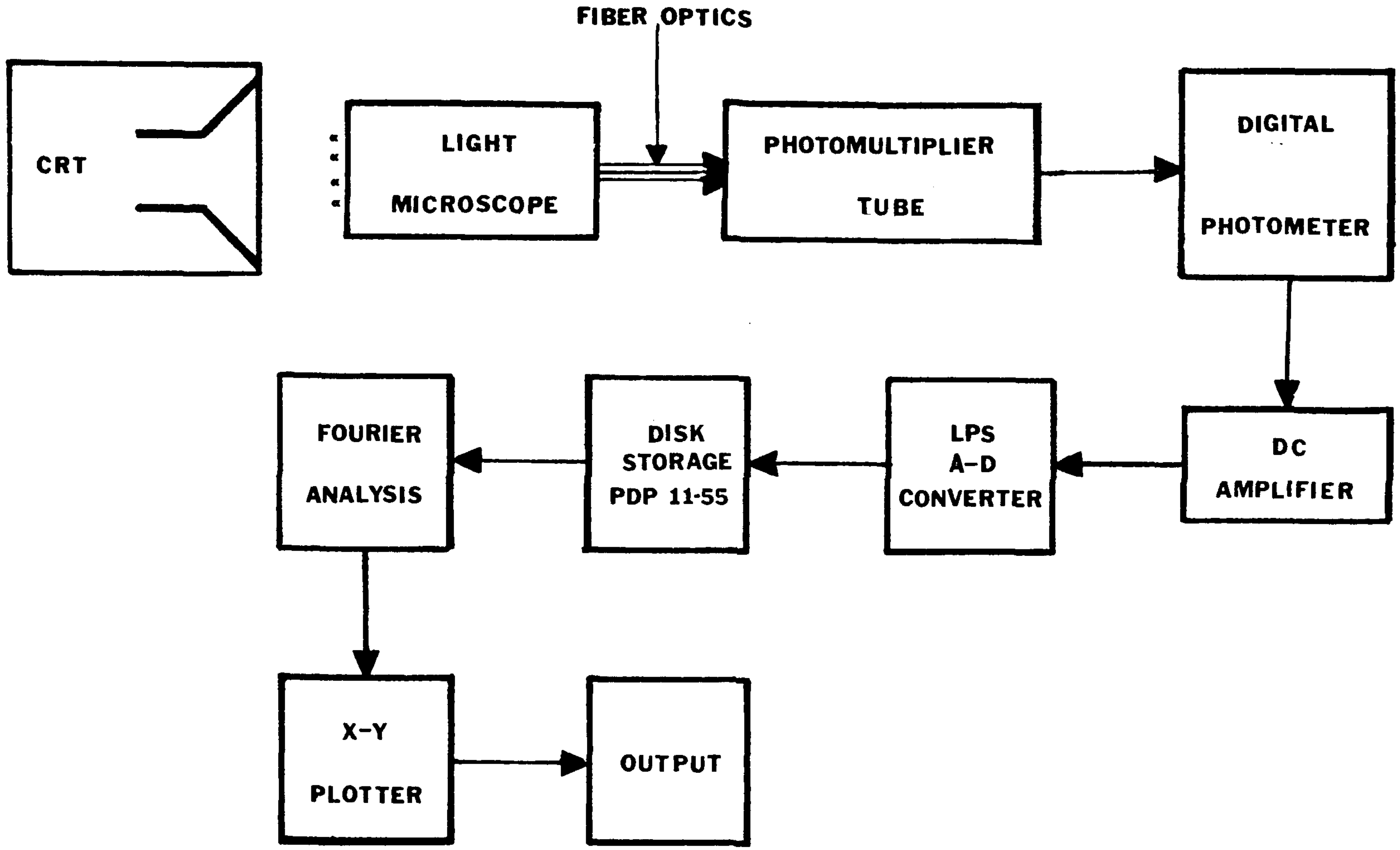

Figure 1. Schematic diagram of data collection and reduction.

locations on the display screen to account for local phosphor irregularities. Further, the LSF scans were obtained in both horizontal and vertical dimensions.

The procedure for all scans was as follows. The microscope was positioned at the center of a raster line and focused. The program SCAN was initiated and the scanning eyepiece traversed the 10-mm sampling range in the display plane. For the horizontal scans, the slit aperture was aligned perpendicular to the raster lines. For the vertical scans, the slit aperature was aligned parallel to the raster lines. The sampling rate employed was 1000 Hz.

Data analysis. The data collected from the horizontal and vertical photometric scans represent a two-dimensional function composed of discrete points. A discrete Fourier analysis (DFA) was performed on both the horizontal and vertical scan profiles using the subroutine FORIT from an IBM scientific subroutine package.

The quantitative measures of display resolution (metrics) for the 10 CRT-TED systems are the area under the system MTF (MTF), the visually-weighted MTF area (VMTF), the variance or squared spatial frequency (SSF) measure, and the Equivalent Passband (EP). These metrics are defined as:

$$MTF = \int_0^{Ny} M(f) \cdot df \qquad (1)$$

where:

$M(f)$ = the MTF at spatial frequency f in cycles/inch,

Ny = the Nyquist limit;

$$VMTF = \int_0^{18} M(f)\ [T(f)] \cdot df \qquad (2)$$

where:

$T(f)$ = the MFT of the human visual system; and

$$SSF = \int_0^{Ny} M(f)\ (f^2) \cdot df, \qquad (3)$$

where:

f = spatial frequency variable, and

$$EP = \int_0^{Ny} [M(f)]^2 \cdot df. \qquad (4)$$

The quantitative measures of display noise (metrics) for the 10 CRT-TED systems are the area under the Weiner spectrum (WS), the area under the visually weighted Weiner spectrum (VWS), and the root mean square (RMS) luminance variation. These metrics are defined as:

$$\mathrm{RMS} = (s_h^2 + s_v^2)^{1/2}, \tag{5}$$

where:

s = the standard deviation of the horizontal and vertical scan profiles, respectively,

$$\mathrm{WS} = \int_0^{Ny} w(f) \cdot df, \tag{6}$$

where: $w(f) = \sum_{x=0}^{N-1} f(x) \cos(2 xf/N) = j \sin(2 xf/N)$; and

$$\mathrm{VWS} = \int_0^{Ny} w(f) \; [T(f)]^2 \cdot df. \tag{7}$$

Phase II

The second phase of this research employed human subjects to obtain performance data in three generic types of tasks. The three experiments represent different information display and task requirement conditions. Three separate subject groups participated in the three experiments. The same CRT-TED systems used in Phase I were used in this Phase.

The first experiment required subjects to search for,

recognize, and touch a specified alphanumeric (A through Z, 0 through 9) target character embedded within a field of nontarget alpha-characters. The characters were presented in the dot matrix Huddleston font. In addition to the 10 CRT-TED systems, polarity (positive and negative contrast video), matrix size (5 x 7, 7 x 9, and 9 x 11), and field density (1 target character to 35 nontarget characters and 1 target character to 105 nontarget characters) were the manipulated parameters.

The second experiment used a task representing a "real-world" application of TEDs in which a high displayed information density condition exists. Participants were required to assign passengers to seats on an aircraft in a simulated passenger seat assignment task. The 10 CRT-TED systems were the only manipulated parameters.

The third experiment also represents a "real-world" application. Participants were required to progress through a series of hierarchical menus in a simulated city information search task. In addition to the 10 CRT-TED systems, polarity was a manipulated parameter.

Phase III

Up to this point, the evaluation of the five TEDs consisted of the recording of objective measures of TED utility. However, perceptual judgement procedures may also represent the utility of TEDs and may have a better prediction of purchase liklihood. Therefore, subjective

assessments of TED utility were collected at the end of each experimental session.

The subjects rated each TED on the basis of its overall usability (USE), the sensitivity (SEN) or responsiveness to touch input, the legibility (LEG) of displayed information and/or graphics appearing under each TED, the brightness (BRI) of displayed infromation and/or graphics appearing under each TED, the esthetic appeal (EA) or appearance of each TED, and the enjoyment (ENJ) of using each TED. Subjects also ranked the TEDs in the order they preferred (from most to least preferred) and the order of purchase preference. Last, subjects were asked for additional comments concerning the TEDs.

Phase IV

To better relate display resolution and display noise to operator performance and subjective assessments of TED utility, an additional (summary) metric of display quality, essentially signal-to-noise ratio, was calculated and may be defined as:

$$STN = \frac{\int_0^{Ny} M(f) \cdot [T(f)] \cdot df}{\int_0^{Ny} 1 + w(f) \cdot [T(f)]^2 \cdot df} \qquad (8)$$

Correlational analyses were then conducted among this summary metric, the display resolution, and display noise metrics computed in Phase I and the human performance and

subjective rating data collected in Phases II and III, respectively. The Pearson product-moment correlation was used to relate CRT-TED display system optical quality to human performance and subjective assessments of TED utility.

RESULTS

Phase I

Transmissivity. As can be seen from Table 1, the Infrared (IR) TED, not being an overlay, has a transmissivity of 1.0. Following in order of decreasing transmissivity are the Acoustic Ranging (AR); the Conductive Film (CF) TED; the Capacitive (CA) TED; and the Cross-Wire (CW) TED. (The CW TED was combined with an anti-glare neutral density filter, which contributed to the lower transmissivity value.)

Low frequency modulation. The low spatial frequency modulation values listed in Table 2 were used to scale the MTF values obtained from analyzing the LSF scans of the spatial line pattern target. As can be seen from Table 2, the low spatial frequency modulation values follow the trend of decreasing values seen in Table 1 of the transmissivity values except for the CA TED. That is, when this TED was applied to the P-31 CRT, a slight increase in low frequency modulation resulted.

Display resolution. Display resolution was characterized by computing several values for the 10 CRT-TED systems. The MTF, the visually weighted MTF (VMTF), the squared spatial frequency (SSF), and the equivalent passband (EP) were computed for both horizontal and vertical LSF scans.

TABLE 1

Transmissivity Values for the Five TEDs

		TED		
IR	AR	CF	CA	CW
1.00	0.89	0.61	0.60	0.33

TABLE 2

Low Frequency (Normalizing) Modulation Values

			TED		
CRT	IR	AR	CF	CA	CW
P-4	0.848	0.831	0.762	0.758	0.600
P-31	0.937	0.930	0.890	0.897	0.821

The horizontal and vertical LSF scan profiles and corresponding MTFs for the five TEDs mounted individually on the P-4 CRT are illustrated in Figures 2 and 3, respectively. Similarly, the horizontal and vertical LSF scans profiles and corresponding MTFs for the five TEDs mounted individually on the P-31 CRT are illustrated in Figures 4 and 5, respectively. Note that the MTF plots have been normalized to the low frequency modulation levels listed in Table 2.

As can be seen from Figures 2 through 5 and Table 1, as TED transmissivity decreased, display modulation decreased. In addition to reducing overall display modulation, the TEDs introduced varying amounts of luminous flare or spreading of displayed data. This luminous flare is evidenced by the inflection points at low luminance along some of the LSF curves, most notably the AR, CF, and CW TEDs.

The reduction in display modulation is most pronounced at the higher spatial frequencies. The MTF plots indicate differential imaging capabilities between the P-4 and P-31 phosphor CRTs. That is, the P-31 phosphor CRT is associated with greater display modulation than is the P-4 phosphor CRT.

Table 3 (horizontal scans) and Table 4 (vertical scans) summarize the quantitative measures of resolution for the 10 CRT-TED systems. From these tables it can be seen that the VMTF follows the same pattern of decreasing modulation as does the non-visually weighted MTF. Further, and in direct

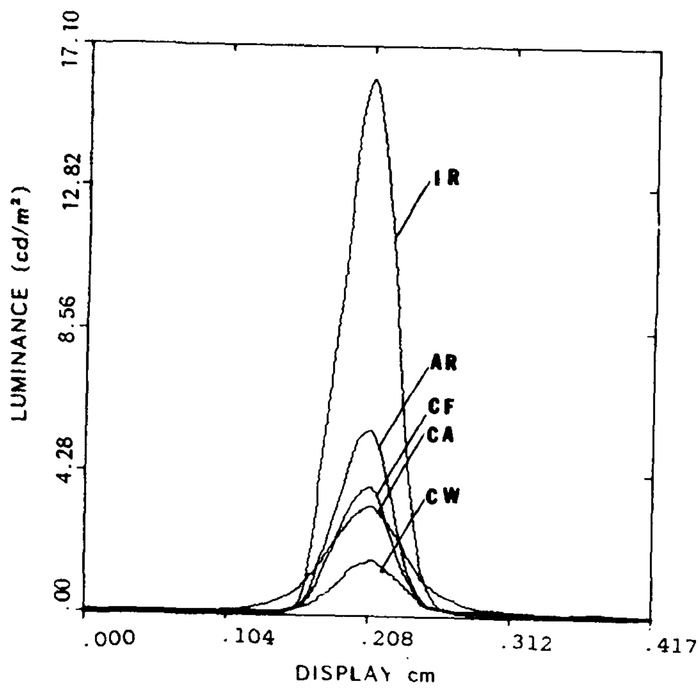

Figure 2a. Horizontal LSF scan profiles.

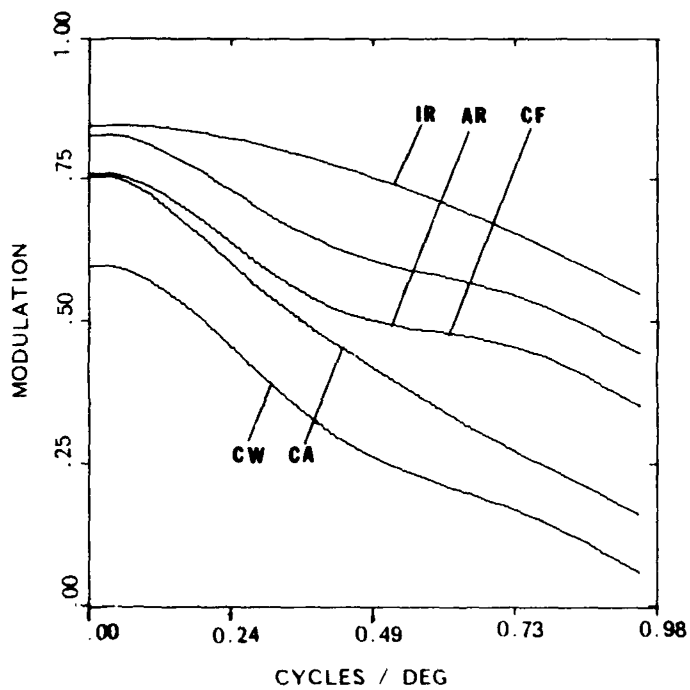

Figure 2b. Corresponding MTF plots for the five TEDs mounted on the P-4 CRT.

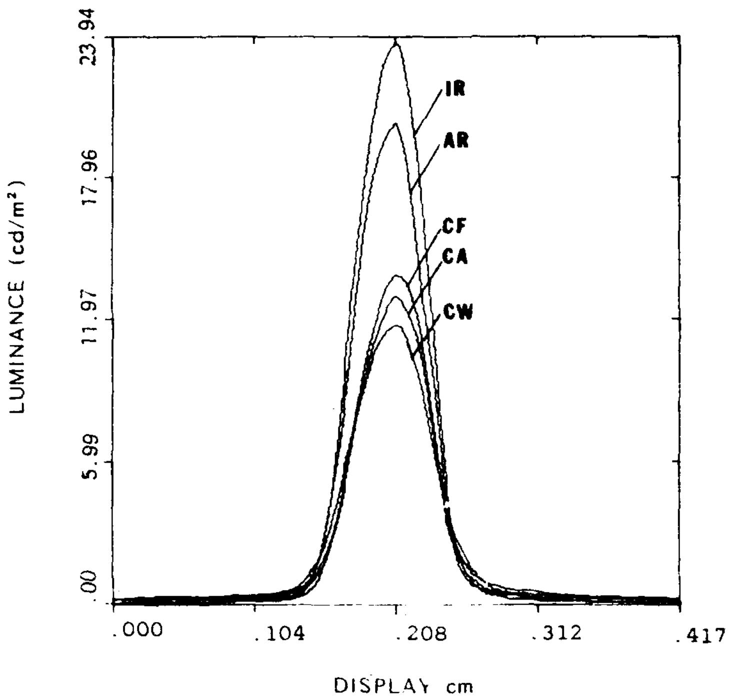

Figure 3a. Vertical LSF scan profiles.

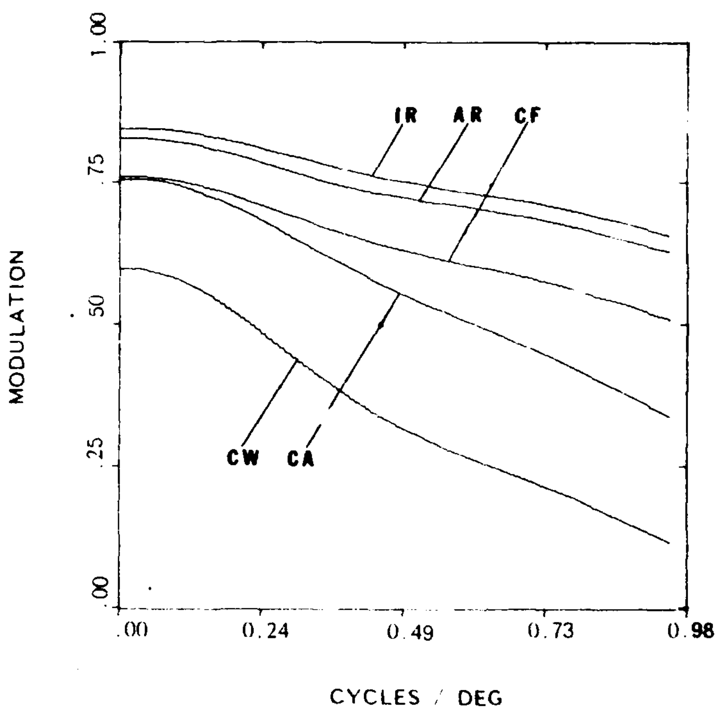

Figure 3b. Corresponding MTF plots for the five TEDs mounted on the P-4 CRT.

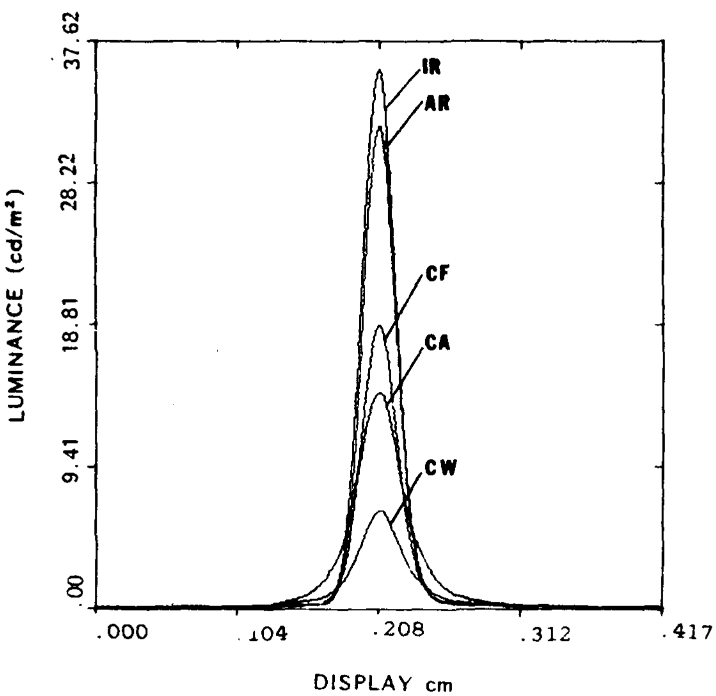

Figure 4a. Horizontal LSF scan profiles.

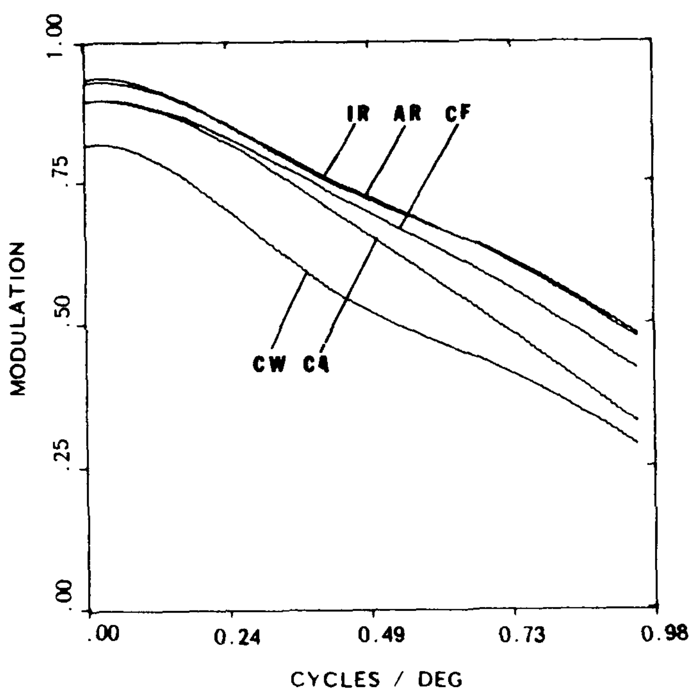

Figure 4b. Corresponding MTF plots for the five TEDs mounted on the P-31 CRT.

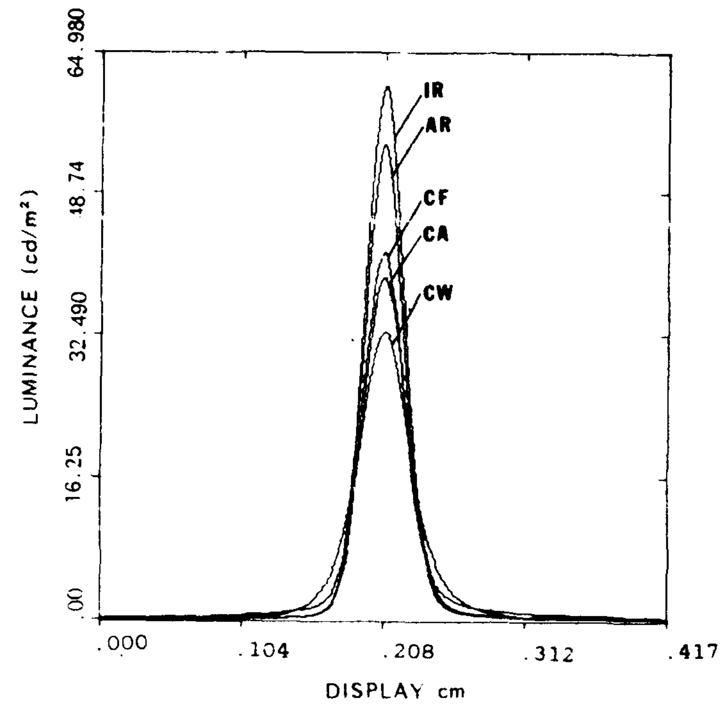

Figure 5a. Vertical LSF scan profiles.

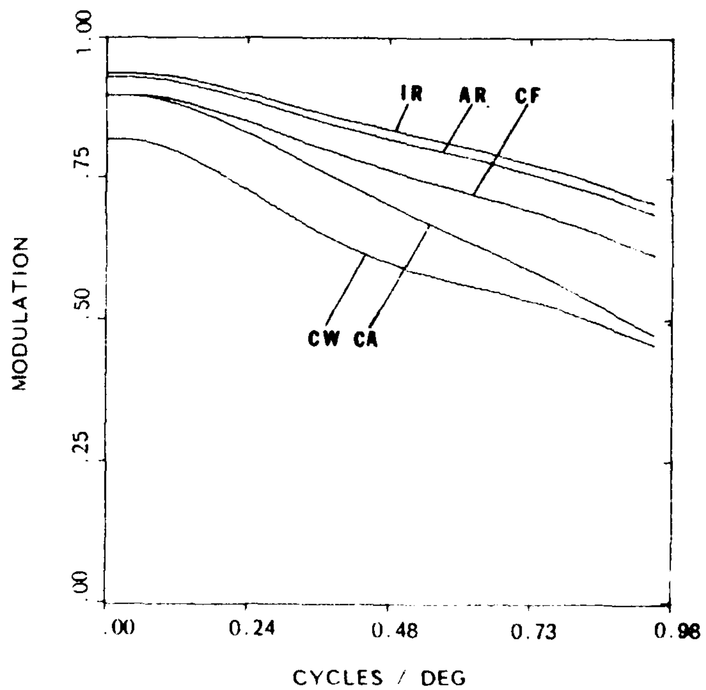

Figure 5b. Corresponding MTF plots for the five TEDs mounted on the P-31 CRT.

relation, the SSF and EP metric values duplicate these trends. Across the metrics the P-31 CRT is generally better than the P-4.

Display noise. The results of the computation of the display noise levels of RMS luminous variation, Wiener noise spectrum (WS), and the visually weighted Wiener spectrum area (VWS) are summarized in Table 5. The P-4 CRT has lower RMS luminous variation values than does the P-31 CRT. The Wiener spectrum values for the P-31 CRT indicate lower noise power than for the P-4 CRT except with the CW TED. The different results noted for the CW TED may in part be due to the presence of the high spatial frequency conductive wires embedded in the overlay. Further examination of Table 5 indicates that the TEDs did not add to display noise. The CW-P-31 CRT-TED sytem increased display noise over the CW-P-4 system. Of course, the P-31 CRT was operated at a higher luminance level than the P-4 CRT. Therefore, the contrast between the wires and the background was greater for the p-31 than for the P-4, thus adding a greater amount of display noise. Display noise appears to be determined, to a large extent, by the raster lines and screen phosphor irregularities associated with each CRT. Most interestingly, display noise levels appear to be related directly to decreases in TED transmissivity.

TABLE 3

Resolution Metrics: Scan Direction Parallel to Raster

METRIC	CRT	TED IR	AR	CF	CA	CW
MTF	P-4	18.68	15.67	12.07	8.55	5.63
	P-31	16.98	16.97	15.31	13.61	11.57
VMTF	P-4	5.25	4.79	4.22	4.02	3.01
	P-31	5.50	5.47	5.31	5.22	4.56
SSF	P-4	7.07	6.03	4.52	3.89	2.13
	P-31	6.40	6.55	5.82	5.24	4.50
EP	P-4	11.81	8.70	6.03	4.31	2.24
	P-31	10.99	11.03	9.72	8.61	6.32

TABLE 4

Resolution Metrics: Scan Direction Perpendicular to Raster

		TED				
METRIC	CRT	IR	AR	CF	CA	CW
MTF	P-4	27.46	26.10	18.99	12.77	6.61
	P-31	29.60	28.62	23.59	18.14	17.18
VMTF	P-4	5.24	5.09	4.59	4.39	3.17
	P-31	5.80	5.74	5.47	5.32	4.74
SSF	P-4	10.28	9.92	6.67	4.84	2.38
	P-31	11.52	11.33	8.92	7.02	6.48
EP	P-4	16.30	15.03	9.95	6.54	2.64
	P-31	19.12	18.29	14.49	10.85	9.01

TABLE 5

Noise Metrics

		TED				
METRIC	CRT	IR	AR	CF	CA	CW
RMS	P-4	2.88	2.56	1.76	1.73	1.01
	P-31	3.99	3.55	2.43	2.40	1.36
WS	P-4	413.05	327.18	153.70	148.70	175.51
	P-31	256.93	203.51	95.61	92.50	256.34
VWS	P-4	115.18	91.23	42.86	41.47	14.01
	P-31	28.88	22.87	10.75	10.40	25.58

Most interestingly, display noise levels appear to be related directly to decreases in TED transmissivity.

Phase II

Experiment 1. The TED effect is illustrated in Figure 6. There is no overall significant difference between the mean number of errors recorded for subjects using the IR and CA TEDs ($p > .05$). Significantly ($p < .05$) fewer errors were made with the IR and CA TEDs than with the CW, AR, and CF TEDs. Also, the difference between the CW and AR TEDs was not significant ($p > .05$). Lastly, operators made a greater number of errors when the CF TED was used than when any of the other TEDs were used ($p < .01$).

The character size effect is illustrated in Figure 7. When the 9 x 11 character size was displayed, operators made a greater number of errors than when either the 5 x 7 or the 7 x 9 dot matrix sizes were presented ($p < .05$). The mean number of errors made by operators when the 7 x 9 character size was displayed was not different from the mean number of errors made when the characters were presented in the 5 x 7 dot matrix size ($p > .05$).

The mean time (MT) to complete 10 trials was longer when the target-to-nontarget ratio was 1 to 105 ($p < .01$) than when the target-to-nontarget ratio was 1 to 35. The TED effect on mean time is illustrated in Figure 8. The MTs recorded for operators using the CF, CW, AR, and IR TEDs are not significantly different ($p > .05$). However, the MT for

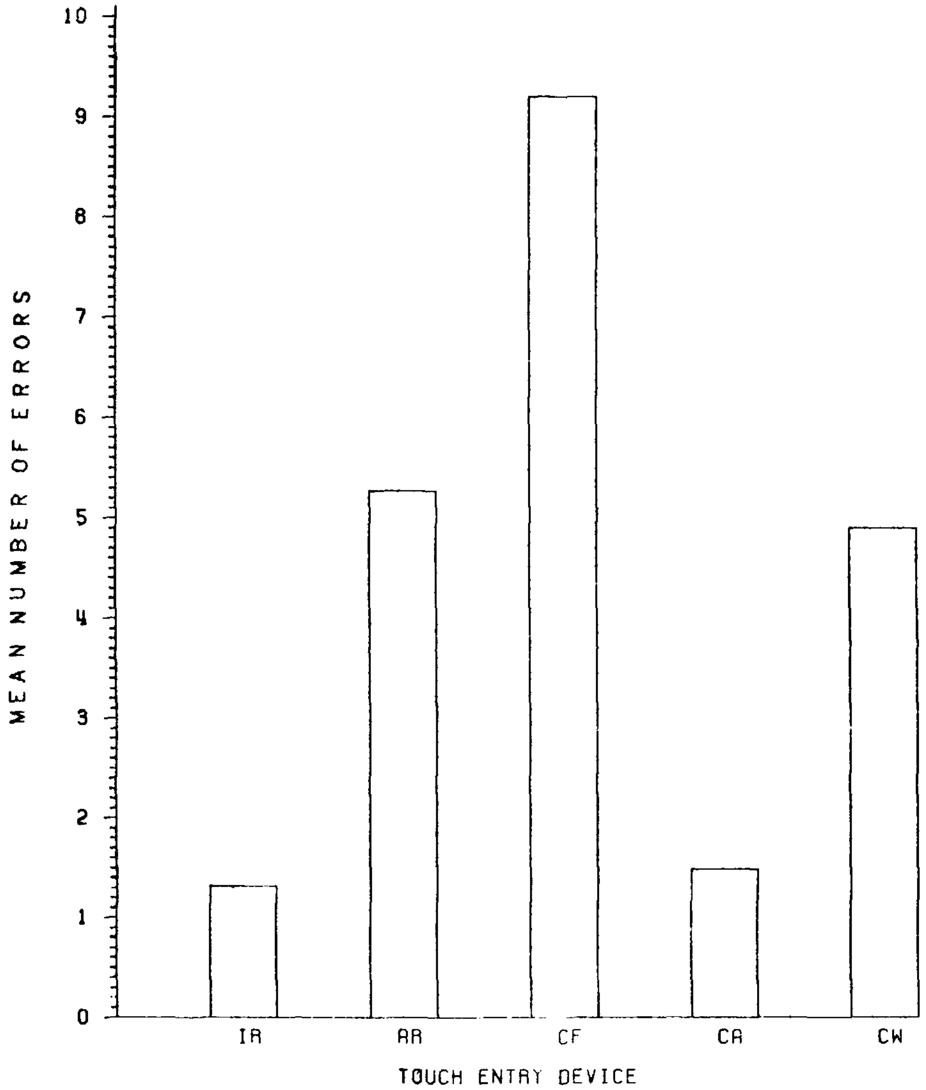

Figure 6. TED main effect for mean number of errors.

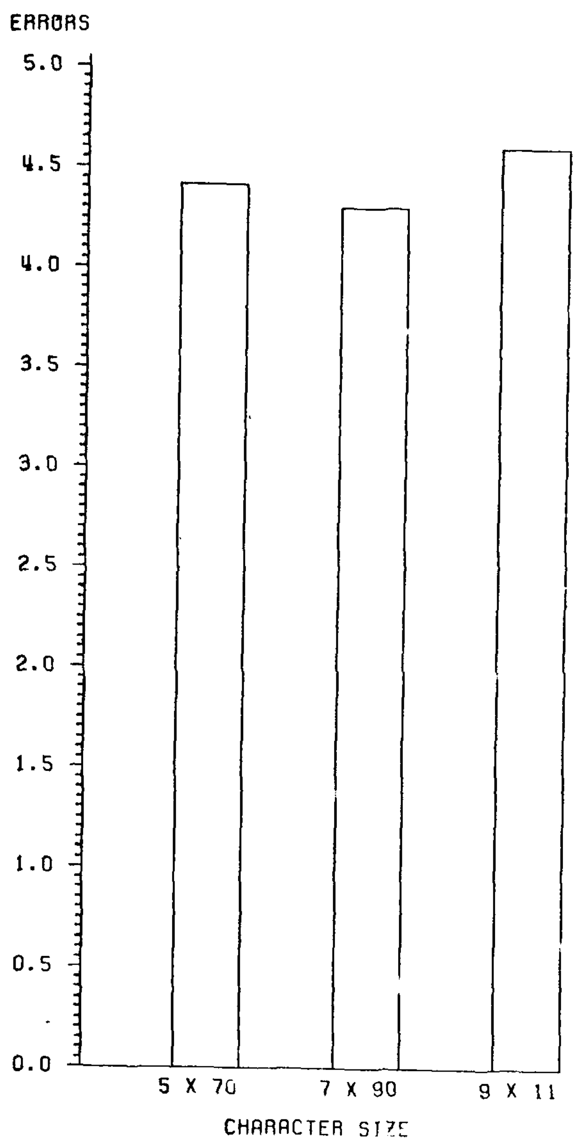

Figure 7. Character size (C) main effect for mean number of errors.

operators using the CA TED was significantly longer than when the other TEDs ($p < .05$) were used.

Experiment 2. The response measures of the number of seat assignment errors, mean time (MT) to complete a single passenger seat assignment, and the total time (TT) to complete the passenger seat assignment task with each TED were evaluated. There are no statistically significant main effects or interactions ($p > .2$) for the number of errors made on this task.

The monitor effect on mean time is illustrated in Figure 9, which indicates that longer MTs were recorded for operators using the the P-31 CRT than for operators using the P-4 CRT ($p < .01$).

The TED effect, illustrated in Figure 10, shows that there is no overall significant difference among the CW, IR, CF, and CA TEDs ($p > .05$). The MT for operators using the AR TED is significantly greater than the MTs for operators using either the CW or IR TEDs but not significantly longer than the MTs for operators using either the CF or CA TEDs ($p > .05$).

The evaluation of the total time to complete the passenger seat assignment task resulted in effects similar to that of the mean time response measure.

Experiment 3. The number of menu selection errors and the total time (TT) to complete the city information task were evaluated.

There are no overall significant differences among the

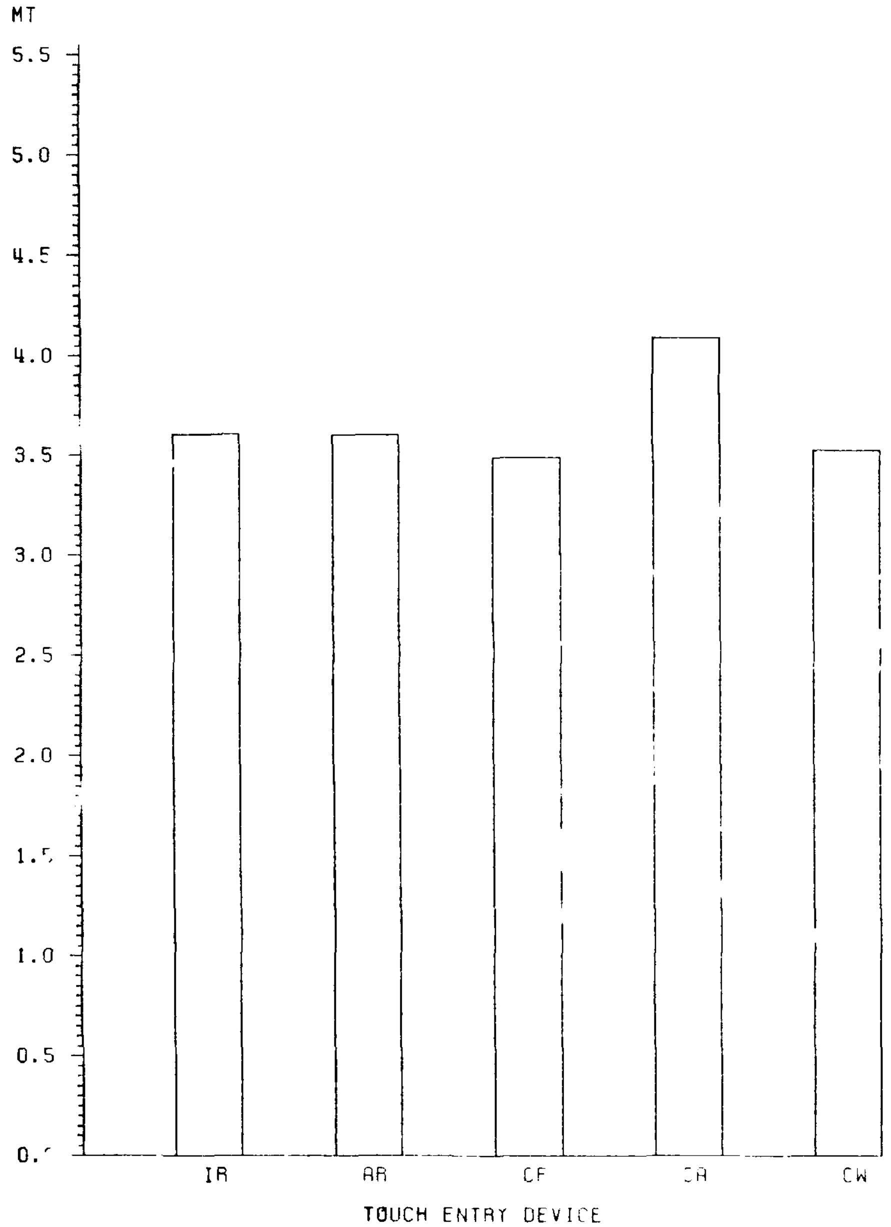

Figure 8. TED main effect for Experiment 1 mean time.

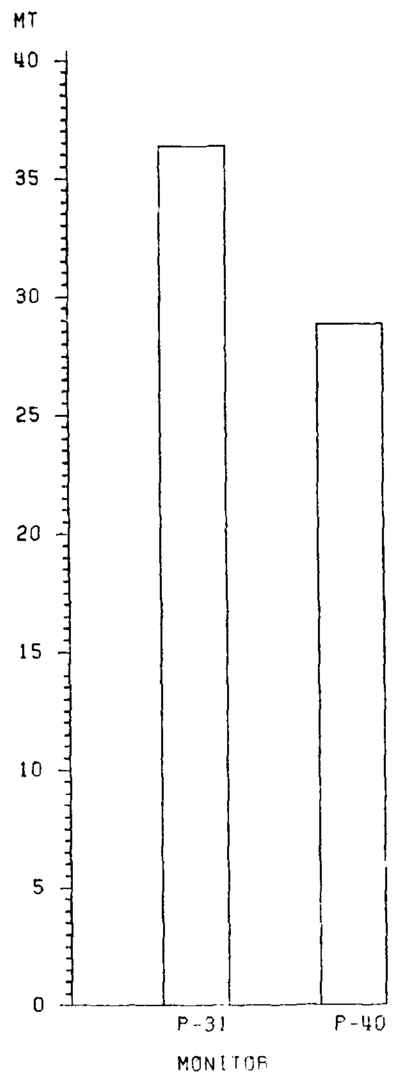

Figure 9. CRT main effect for Experiment 2 mean time.

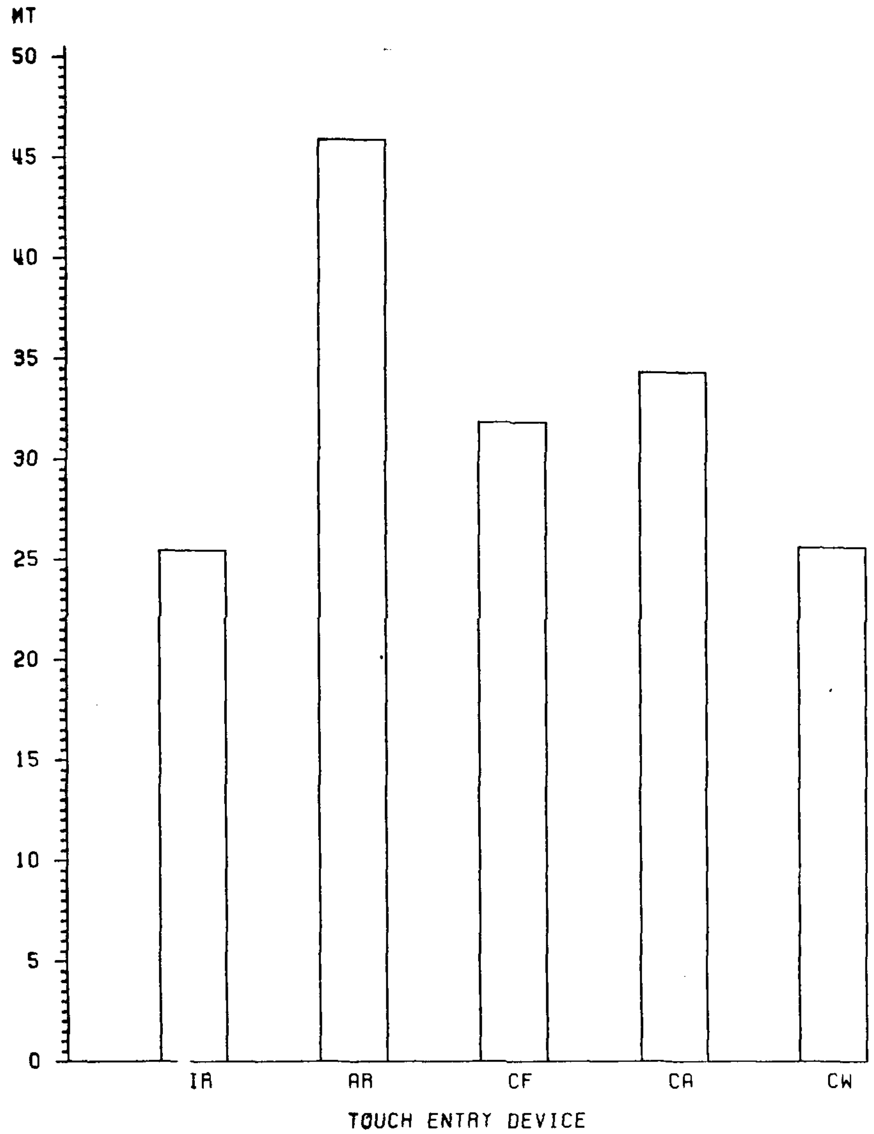

Figure 10. TED main effect for Experiment 2 mean time.

number of menu selection errors using the CA, IR, CW, or AR TEDs ($p > .05$). However, the number of errors for the CF TED was significantly greater than the numbers of errors for the other TEDs ($p < .01$), as shown in Figure 11.

Phase III

The results of the ratings of (1) the brightness of displayed information and/or graphics appearing under each TED and (2) the sensitivity or responsiveness of each TED to touch input were "mapped" to conform to the equivalent rating scale values of (3) the legibility of displayed information and/or graphics appearing under each TED, (4) the overall usability of each TED, (5) the enjoyment of using each TED, and (6) the esthetic appeal of each TED. Further, a "composite" rating value was created by computing the mean value for all ratings.

Experiment 1. The effect of TED was not statistically significant ($p > .05$) for ratings of brightness, enjoyment, esthetic appeal, and the composite rating. For usability and legibility, the main effect of TED was statistically significant.

The effect of TED for the rating of usability is illustrated in Figure 12, indicating that the AR TED was rated lowest on the basis of its usability ($p > .05$). Further, the IR, CF, CA, and CW TEDs received essentially equivalent ratings ($p > .05$) and their ratings are significantly higher than those for the AR TED ($p < .05$).

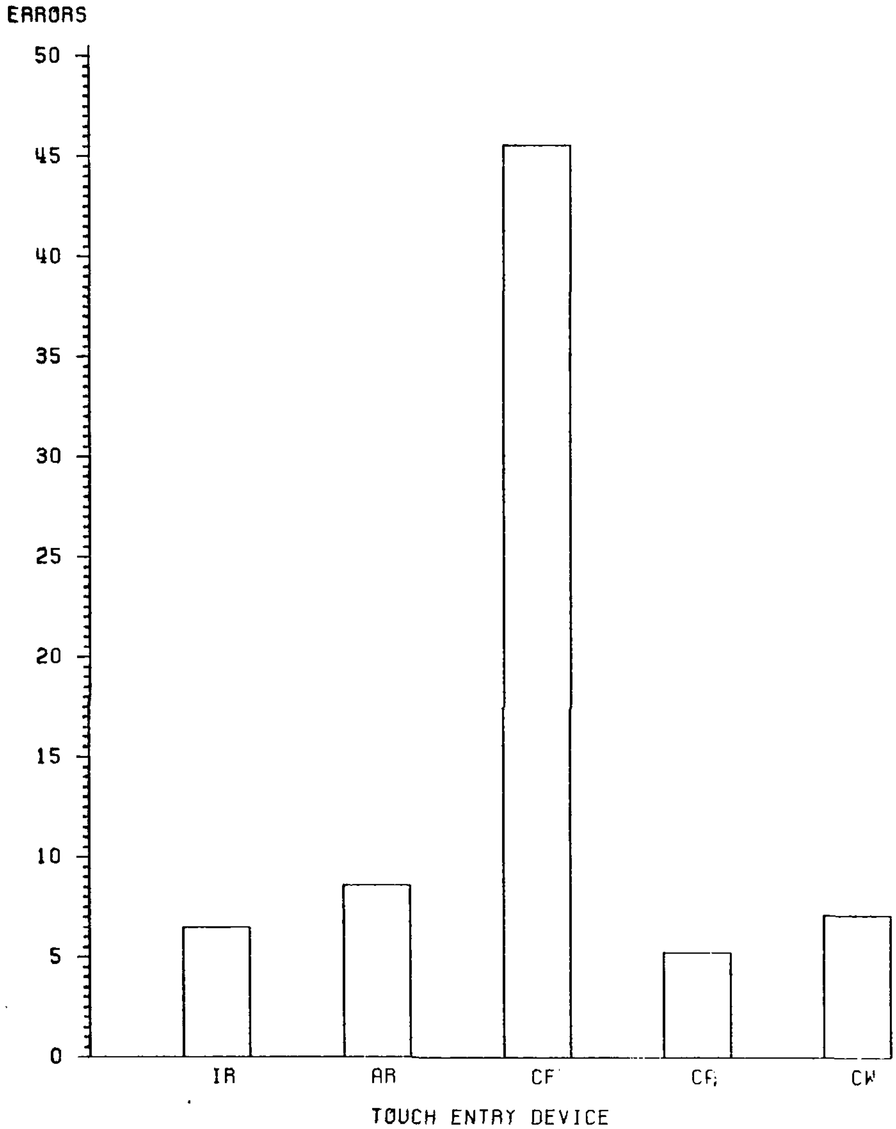

Figure 11. TED main effect for Experiment 3 number of errors.

The effect of TED on legibility, illustrated in Figure 13, indicates that the CA, AR, and IR TEDs received essentially equivalent ratings ($p > .05$). Further, the ratings received by these TEDs were significantly lower than the ratings received by either the CF or the CW ($p < .05$). In addition, the CF and CW TEDs also received essentially equivalent ratings ($p > .05$).

Experiment 2. The effect of TED was not statistically significant ($p > .05$) for brightness, legibility, sensitivity, and esthetic appeal. However, the effect of TED on usability was statistically significant ($p < .05$).

The usability ratings are illustrated in Figure 14 and indicate that the CA, CW, and CF TEDs received higher ratings than did the IR or AR TED ($p < .05$). However, the ratings received by the IR, AR, and CW TEDs were not significantly different ($p > .05$) from one another nor were there significant differences among the ratings received by the CW, CF, or CA TEDs ($p > .05$).

The main effect of TED for the rating of enjoyment indicates the same pattern of results as seen for the usability rating.

The effect of TED for the composite rating is illustrated in Figure 15. The CF and CA TEDs received significantly higher composite ratings ($p < .05$) than did the IR TED. Further, the CA TED received a significantly higher composite rating than did the AR TED ($p < .05$). In addition, the ratings received by the CW, CF, and CA TEDs

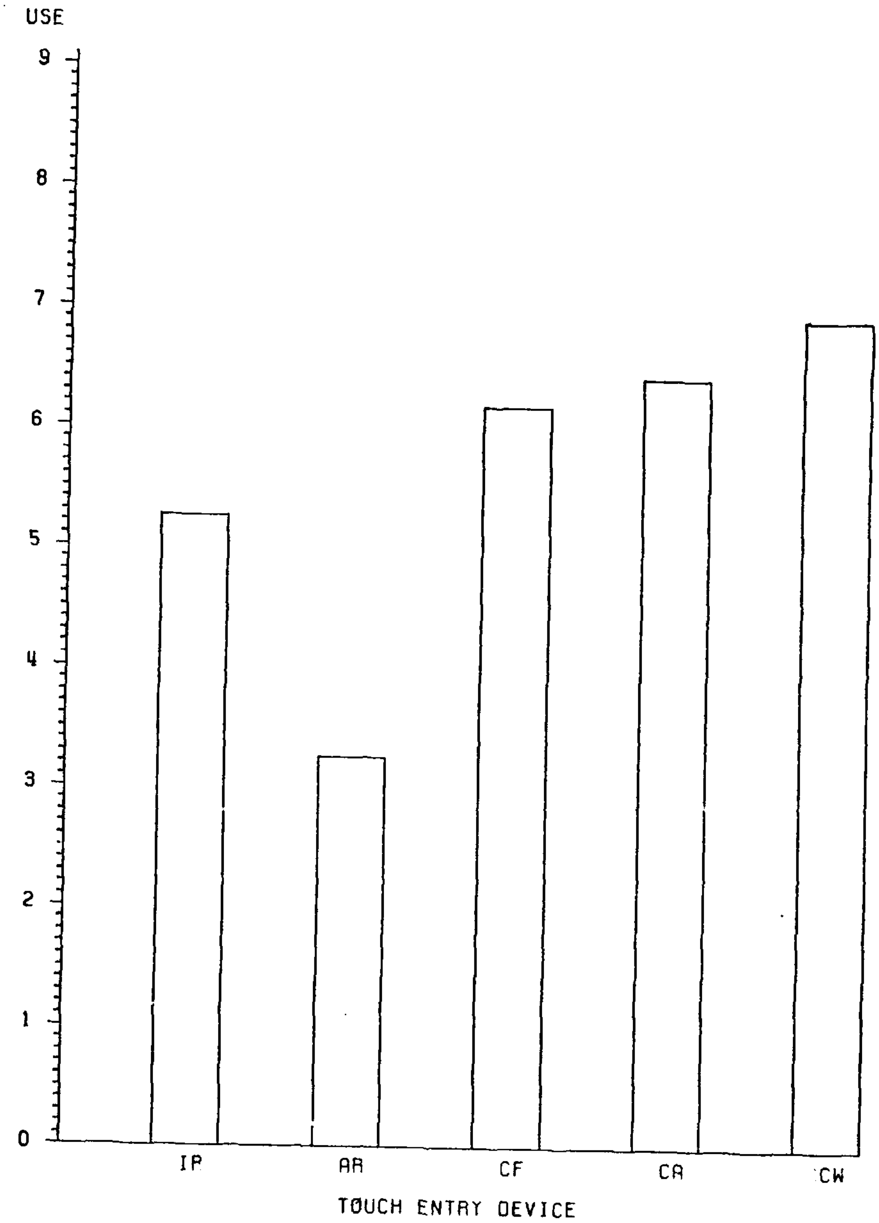

Figure 12. TED main effect for the usability rating.

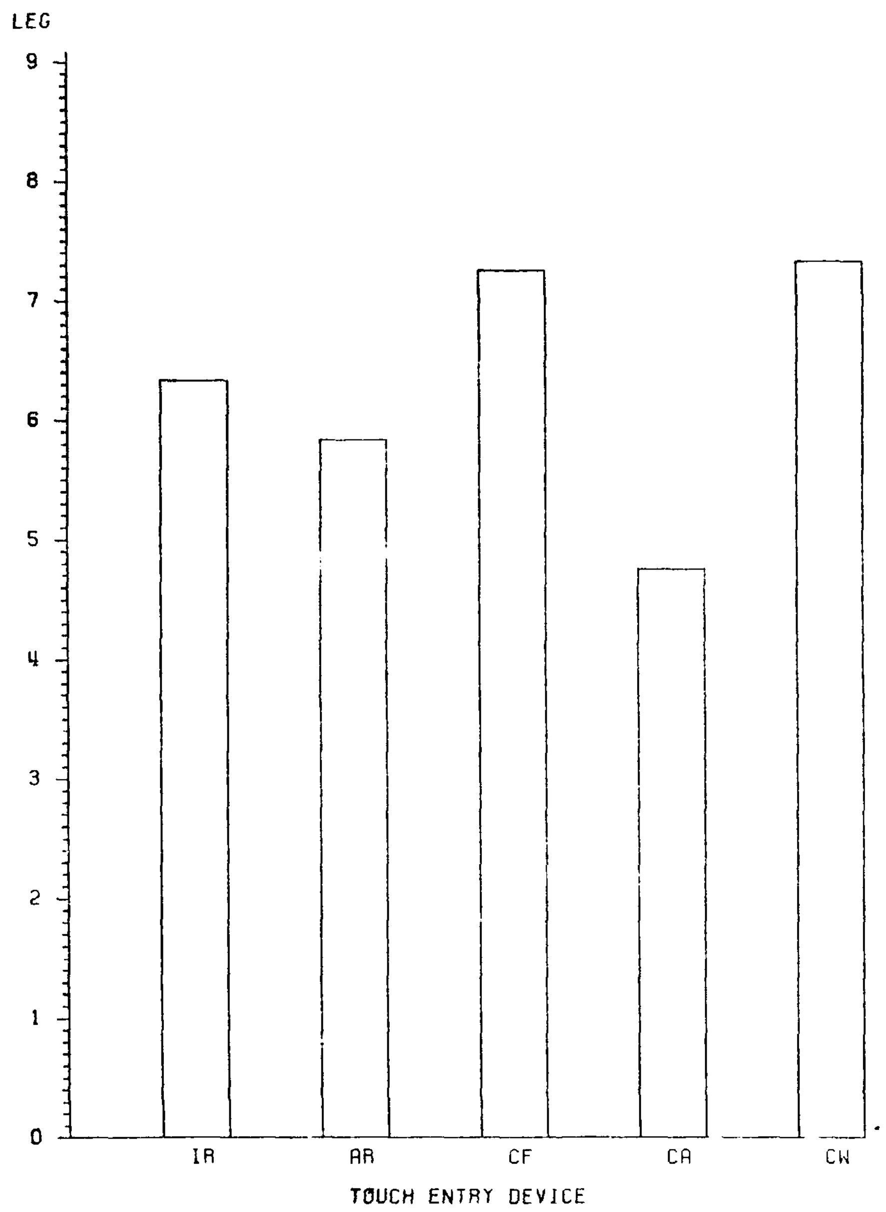

Figure 13. TED main effect for the legibility rating.

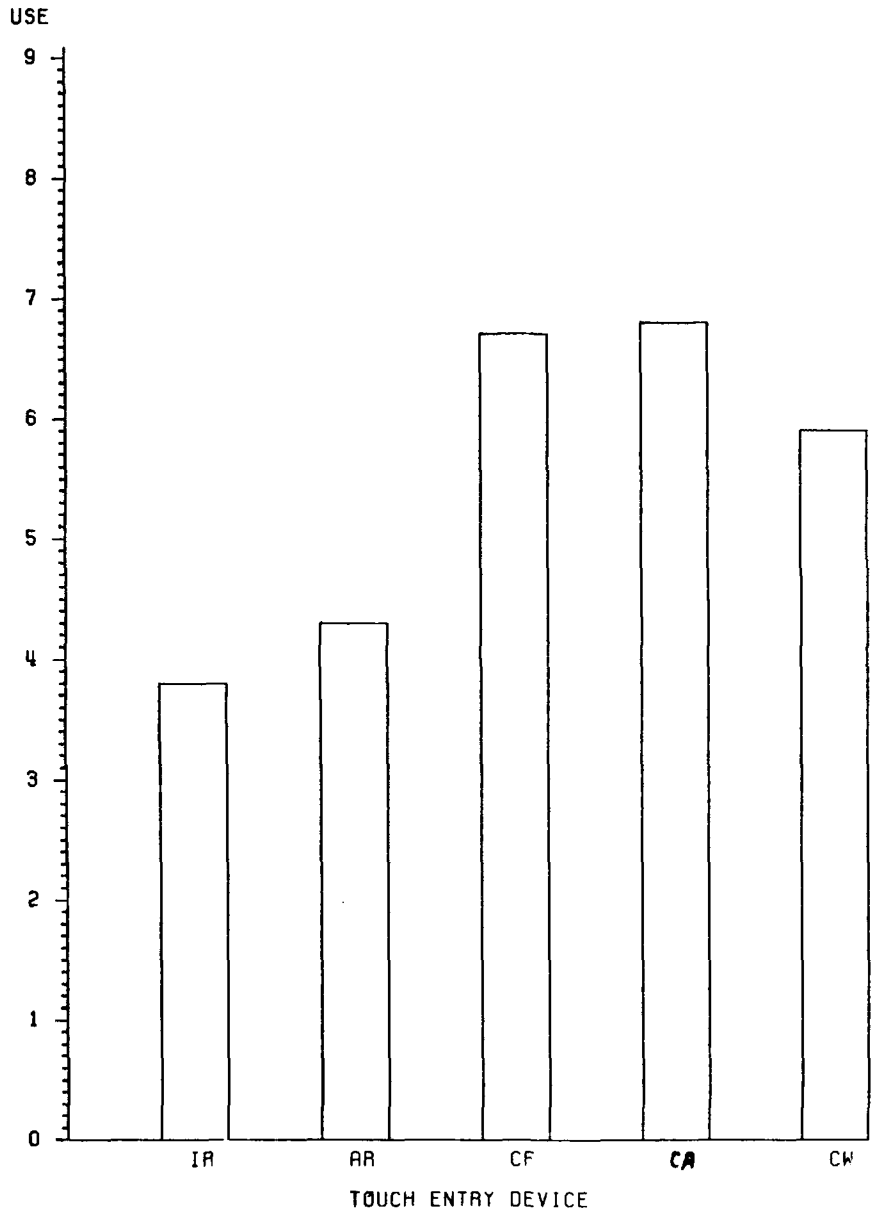

Figure 14. TED main effect for the rating of usability.

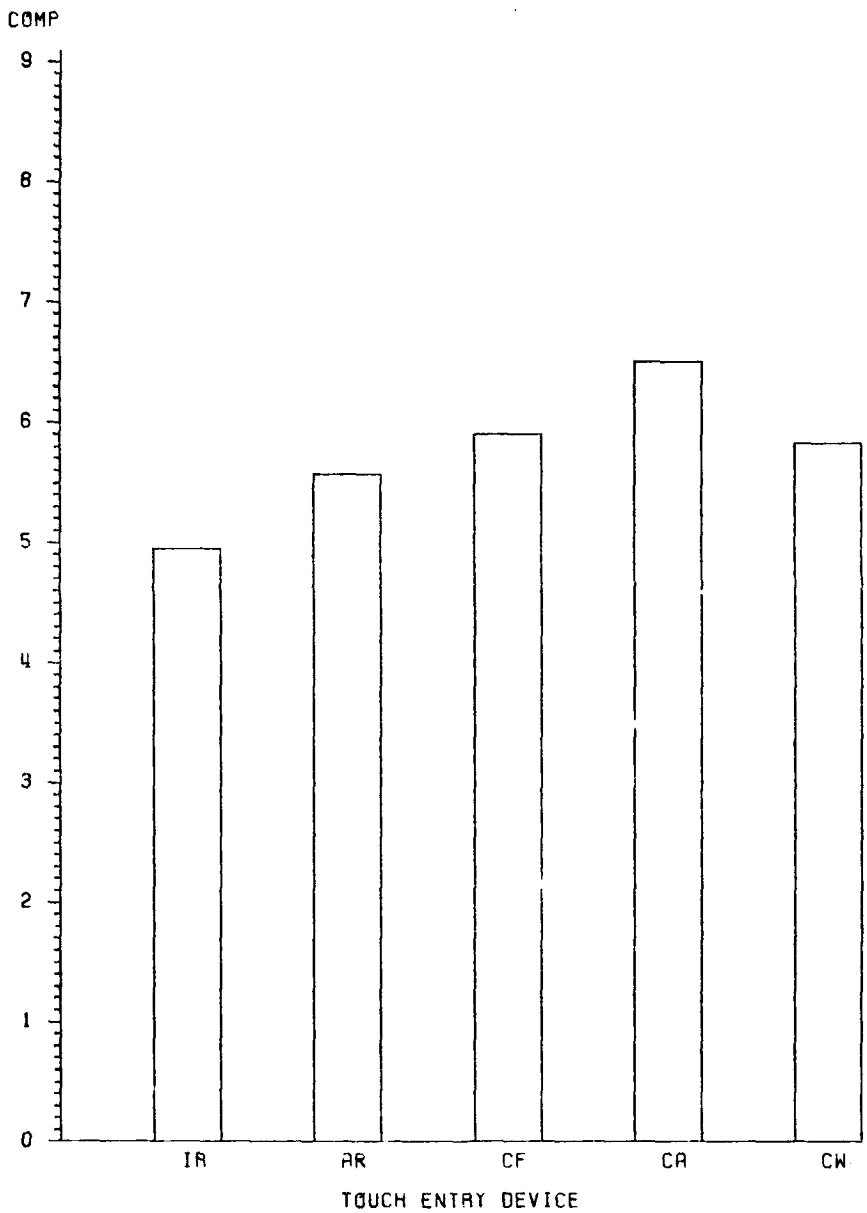

Figure 15. TED main effect for the composite rating.

were not significantly different (p > .05) nor were the ratings received by the AR and IR TEDs.

Experiment 3. The effect of TED was not statistically significant for either esthetic appeal or sensitivity. However, the effect of TED was found to be statistically significant for the ratings of legibility, usability, enjoyment, brightness, and for the composite rating.

The effect of TED for the legibility rating indicates that the CF and IR TEDs received a significantly higher rating (p < .05) than did the CA TED and that the CF TED received a significantly higher rating than did the AR TED (p < .05).

The main effect of TED on usability indicates that the IR, CA, CW, and CF TEDs received significantly higher ratings than did the AR TED (p < .01). Further, the CF TED received a significantly higher rating (p < .05) than did the IR TED. However, the ratings received by the CA, CW, and CF TEDs were not significantly different (p > .05).

The effect of TED for the enjoyment rating duplicates those of the usability ratings.

The effect of TED for the rating of brightness indicates that the CA TED received a significantly higher rating than did either the CF (p < .01) or the CW TED (p < .05). Further, the ratings received by the CF, CW, AR, and IR TEDs were not significantly different (p > .05).

The effect of TED for the composite rating is illustrated in Figure 16. These results indicate that the

IR, CA, CW, and CF TEDs received significantly higher ratings than did the AR TED ($p < .01$).

TED Rankings

In addition to the TED ratings, subjects ranked the TEDs in the order in which they would purchase if in a position to do so and in the order they preferred overall.

Experiment 1. In this experiment, there were no significant TED differences for either the purchase or preference rankings ($p > .05$).

Experiment 2. Operators ranked the P-4 CRT higher ($p < .01$) than the P-31 CRT in the purchase category, suggesting a preference for the white phosphor.

The effect of TED indicates that the AR, CA, IR, and CW TEDs were ranked higher ($p < .01$) for purchasing than the CF TED. Further, the IR and CW TEDs were ranked higher ($p < .01$) than was the AR TED. The CF TED received a higher rank than did the other TEDs ($p < .01$).

The P-4 CRT was ranked higher ($p < .01$) in preference than the P-31, as was found with the rankings of purchase.

Figure 17 indicates that the CA, AR, IR, and CW TEDs were ranked higher in preference than was the CF TED ($p < .01$). Further, the IR and CW TEDs received higher ranks than did the CA TED ($p < .01$). In addition, these TEDs ($p < .05$ and $p < .01$, respectively) were ranked higher than was the AR TED. The CW TED received a higher rank than did the

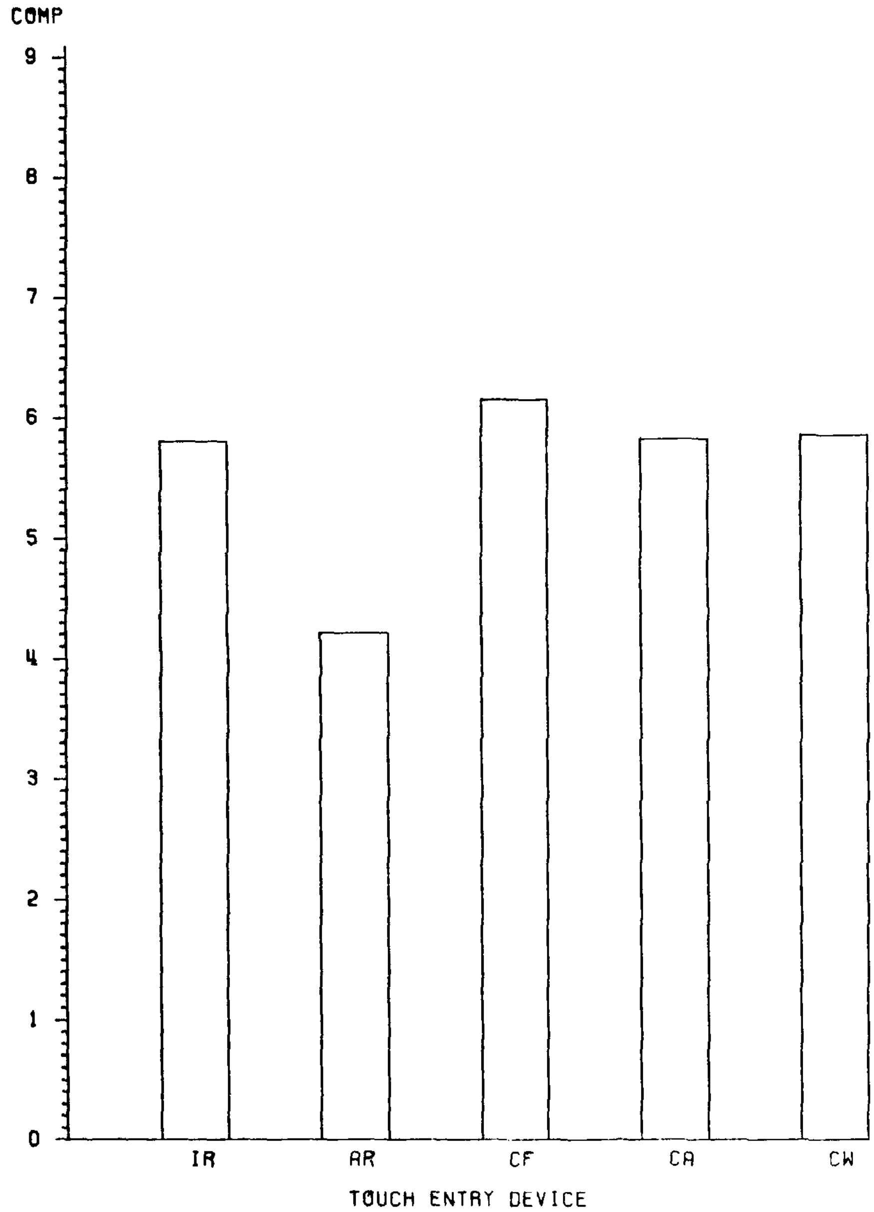

Figure 16. TED main effect for the enjoyment of use rating.

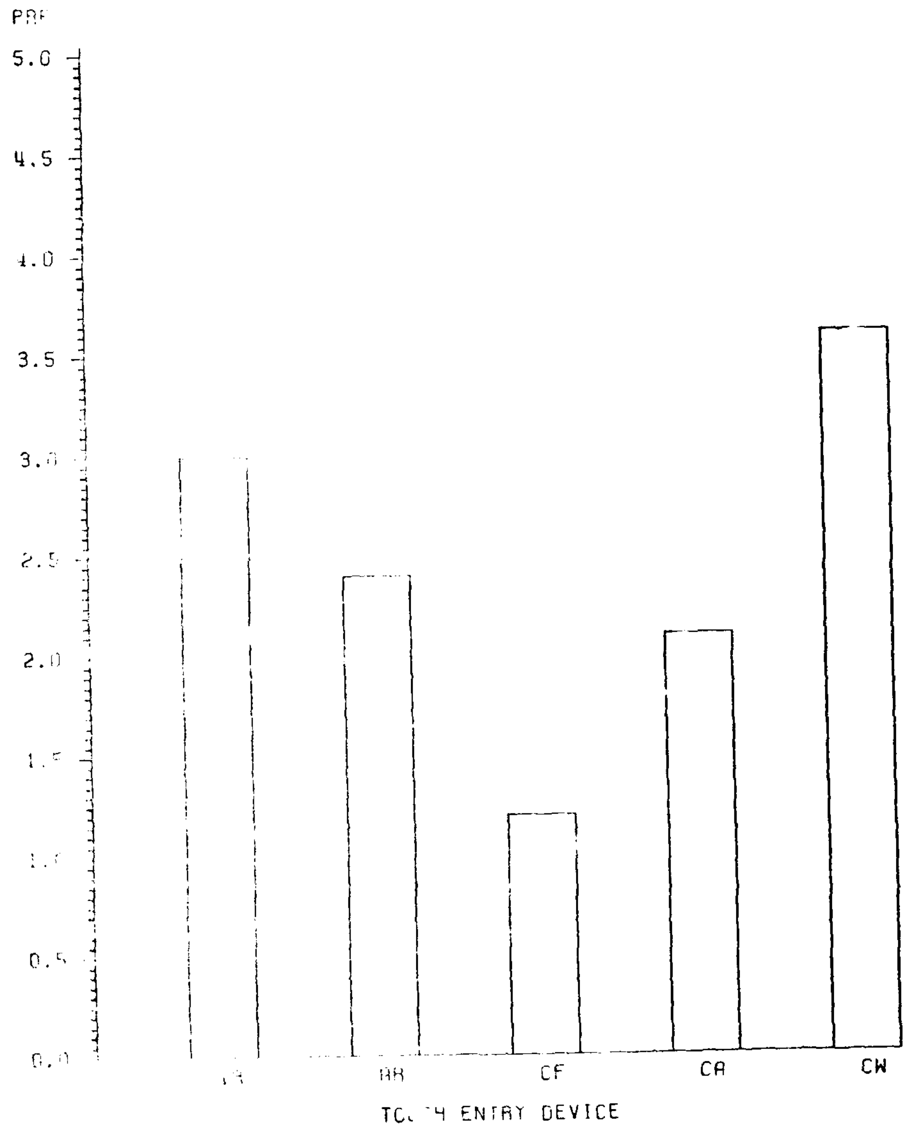

Figure 17. TED main effect for the preference ranking.

other TEDs ($p < .05$). Figure 18 indicates that the CF IR, and CW TEDs were ranked higher for purchase ($p < .01$) than was the AR TED. The results of the analyses for the preference ranking indicates, as did the purchase rankings, that the P-4 CRT received a higher rank than the P-31 CRT ($p < .01$).

Experiment 3. Figure 19 indicates that the CW, CF, and IR TEDs were ranked higher in preference than either the AR or CA TEDs ($p < .01$). The AR and CA TEDs received essentially equivalent ranks, as did the IR, CF, and CW TEDs ($p > .05$).

Phase IV

Correlational analyses were conducted in an attempt to relate the quantitative measures of display system quality collected in Phase I to user performance measures and subjective assessments of TED utility collected in Phases II and III (Experiment 1).

For the TEDs mounted on the P-31 CRT, the Wiener Spectrum area (WS) and the Visually Weighted Wiener Spectrum area (VWS) were significantly (negatively) correlated with the response measures of Total Time (TT), Mean Time (MT), Presentation Time (PT), and Reaction Time (RT). That is, as display noise levels were reduced, TT, MT, PT, and RT increased. These results are clearly counterintuitive. In addition, both horizontal (STNH) and vertical (STNV) signal-to-noise ratio metrics were significantly (positive)

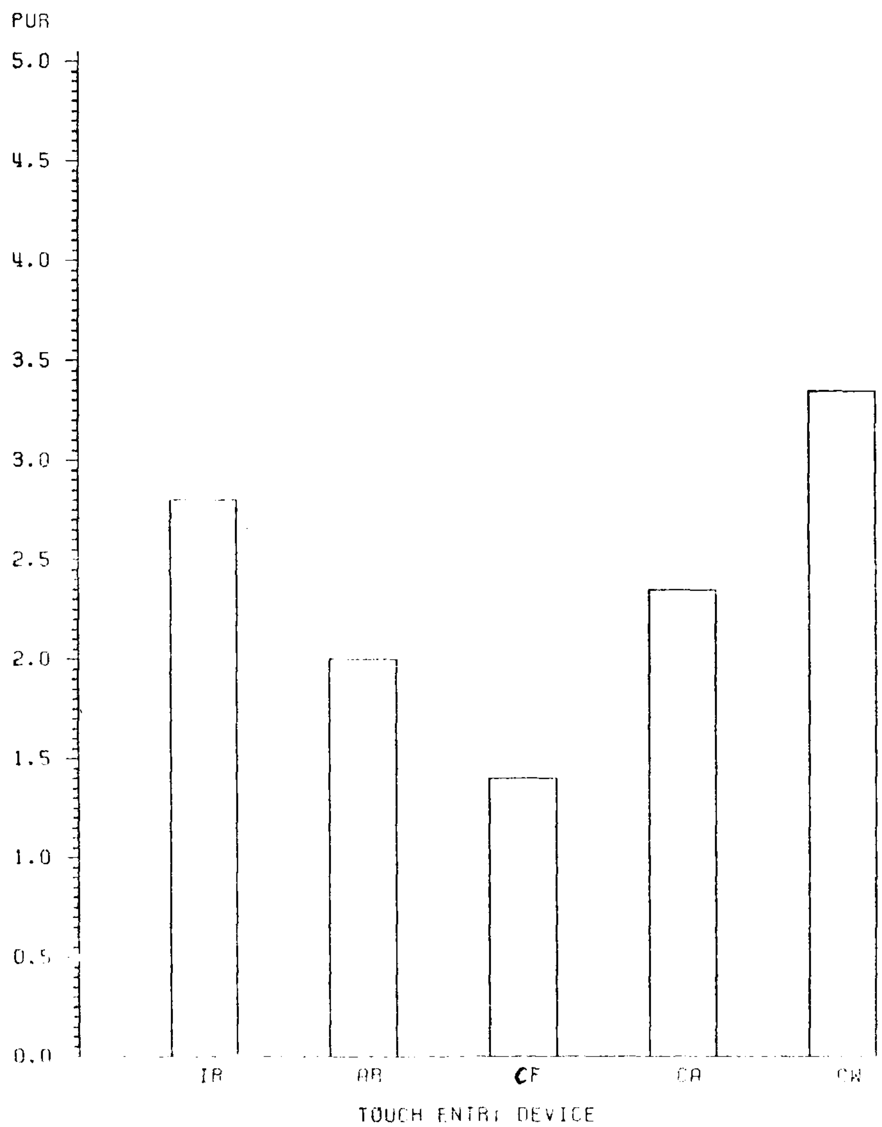

Figure 18. TED main effect for the purchase ranking.

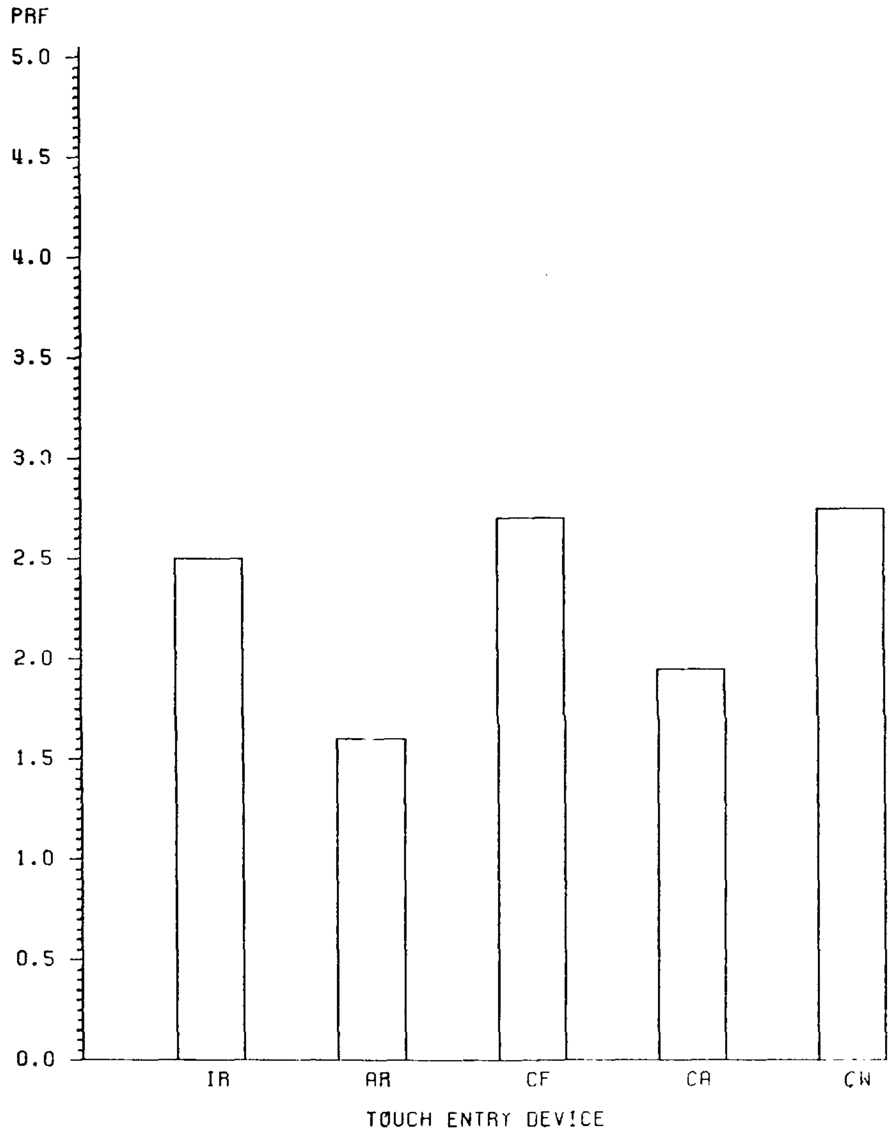

Figure 19: TED main effect for Experiment 3 preference ranking.

correlated ($p < .03$) with TT, MT, PT, and RT. That is, as STN levels increased TT, MT, PT, and RT increased.

The Usability, Brightness, and Composite ratings were significantly (negatively) correlated with both horizontal and vertical MTFs, VMTFs, SSFs, and EPs ($p < .0001$), as well as with RMS noise ($p < .0001$ for Usability and Composite, $p < .0003$ for Brightness) and VWS ($p < .05$). That is, as display resolution and display noise increased, subjects rated the TEDs lower on the basis of Usability, Composite Utility, and Brightness. The resolution results are also counterintuitive.

A different set of results for the rating of Enjoyment of Use resulted. Specifically, a significant positive correlation between ENJ and display resolution values occurred ($p < .0001$ for both horizontal and vertical scan based MTFs, SSFs, EPs, and the NMTFV, and $p < .0012$ for VMTFH). That is, as display resolution increased, ratings of Enjoyment of Use increased. In addition, ENJ was also significantly (positively) correlated with the display noise values of RMS ($p < .0001$), WS ($p < .250$), and VWS ($p < .0055$), indicating that as display noise increased ratings of ENJ increased. Further, the rating of ENJ was also significantly correlated with both horizontal ($p < .0111$) and vertical ($p < .0121$) signal-to-noise ratios. Specifically, ENJ was negatively correlated with STNH and STNV and indicates that as signal-to-noise levels increased ratings of Enjoyment of Use decreased, another

counterintuitive result.

The results of the correlations between display system quality and the ratings of Esthetic Appeal and Legibility and both Purchase and Preference rank orderings indicate that the ratings of EA and LEG follow patterns similar to those of the Purchase and Preference ranks. Specifically, the rating of EA was significantly (negatively) correlated with the display resolution metrics (p < .0001 for both horizontal and vertical MTFs, SSFs, EPs, and the VMTFV, and p < .0011 for VMTFH). That is, as display resolution increased, subjective assessments of EA decreased. Further, EA was significantly (negatively) correlated with the display noise measures of RMS (p < .0001), WS (p < .0416), and VWS (p < .0106), indicating that as display noise levels increased ratings of EA decreased. In addition, the rating of Esthetic Appeal was significantly (positively) correlated with both horizontal (p < .0121) and vertical (p < .0126) signal-to-noise ratios, as well. These results indicate that as STN levels incresed, the TEDs were rated higher on the basis of EA, a result which is logical and reasonable.

A significant (negative) correlation between Legibility and display resolution (p < .0002) indicates that as TED-CRT display system resolution increased, ratings of TED-CRT display system legibility decreased.

As with the rating of Enjoyment of Use, both purchase and preference ranking values were significantly (positively) correlated with display system optical quality

and display system noise level values. Specifically, the purchase rank was significantly correlated with the values for MTFH, SSFH, MTFV, SSFV, EPV, VWS ($p < .0001$), VMTFH ($p < .0403$), EPH ($p < .0010$), RMS ($p < .0003$), and WS ($p < .0007$). That is, as display resolution and display noise increased, the TEDs were ranked higher in order of purchase. A similar pattern of results is indicated for the preference ranks.

Both Purchase and Preference ranks were significantly (negatively) correlated with both the horizontal and vertical ($p < .0006$) signal-to-noise ratio metrics. These results indicate that as STN values decreased, subjects ranked the TEDs higher on purchase and preference, another unpredictable result.

The results of the correlations between the qualitative measures of display system quality and operator performance for the TEDs mounted on the P-4 CRT indicate a somewhat different pattern of results. This difference will be discussed later.

DISCUSSION

Phase I

Display resolution. The quantification of display resolution indicates that four of the five TEDs degraded resolution by lowering overall modulation. That is, with decreases in TED transmissivity, TED-CRT system modulation was reduced. Therefore, the IR TED permits the highest resolution capability.

In relation to this "baseline" condition, display resolution for the P-31 CRT was attenuated by approximately ten percent by the AR, forty percent by the CF and CA, and sixty percent by the CW TED. A similar attenuation of display resolution is attributable to the CF, CA, and CW TEDs mounted on the P-4 CRT. CRT-TED display system modulation was lowest when the CW was applied. Display resolution was best for the P-31 CRT.

Display noise. The TEDs evaluated in this research did not add to display noise in terms of RMS luminance nonuniformity. Quite to the contrary, all four (AR, CA, CF, and CW) TEDs actually reduced display noise in relation to the baseline IR TED. This is consistent with the transmissivity data in that, as TED transmissivity decreased, the range of luminance variation on the display screen was attenuated.

The WS metric, as a measure of noise power, indicates a similar reduction in display noise across the TED systems

except in the case of the CW TED. Here, noise levels associated with this TED are relatively high. This increase in display noise is attributed to the presence of the double rows and columns of conductive wires. It is interesting that a slightly different pattern of results occurred for the CW TED mounted on the P-31 than for the same TED mounted on the P-4 CRT. Recall that the P-4 CRT was operated at a higher luminance level than the P-31 CRT. As a result, the lower luminance level led to a reduction in modulation or noise power for the wires contained in the CW TED.

Further, because the RMS luminance nonuniformity measures added both horizontal and vertical scan profiles in quadrature, the greater modulation measured from the perpendicular scans appears to have masked any effects of the embedded wires of the CW TED evidenced in the WS values computed from scans parallel to the raster lines.

On the basis of the results of Phase I, the IR TED was logically the best, in terms of display resolution, followed respectively by the AR, CF, CA, and CW TEDs. In terms of display noise, the CA was best, followed respectively by the CF, CW, AR, and IR for the low luminance display (P-4). The CA was again best followed respectively by the CF, AR, CW. and IR for the high luminance display (P-31).

Visual impressions of the TEDs are generally represented by subject comments collected during Phase II and are discussed in relation to subjective assessments of TED utility. However, several observations are presented

here.

First, the gold film of the CF TED caused characters to appear amber (P-4) or brown (P-31). This effect was seen as pleasing to the subjects. In addition, the CA and CW TEDs not only caused the diplayed information to become darker, thus reducing character-background contrast, but under negative contrast conditions introduced "noise" in the form of visible segmentations between touch sites (CA) and occlusive wires (CW). Further, the CA tended to blur displayed images, likely due to the ITO medium fired onto the glass plate overlay.

Phase II

Errors. Although it would be convenient to state that the same or similar pattern of results occurred across the three experiments, this is not the case. There is, in fact, a different ordering of the TEDs from least to most operator errors across the three experiments. Specifically, the best TED in Experiment 1 was the IR, followed by the CA, CW, AR, and CF TEDs, in turn. In Experiment 2, the CF TED was the best, followed by the CW, IR, AR, and CF TEDs. The CA was the best in Experiment 3, followed by the IR, CW, AR, and CF TEDs.

Further, across the three experiments the IR TED was best. Although other authors (Beairsrto et al., 1978) report a parallax problem with the application of this TED to CRTs, such a result was not seen here, and for good

reason. In the study noted above, information was displayed at the edges of the CRT screen. In the experiments conducted in this research, the active touch area of all TEDs was equated. Therefore, the active touch area in these experiments did not include the screen periphery. The CA and CW TEDs were next best although subject comments indicated that the optically defined touch sites interfered somewhat with target acquisition performance across tasks. However, the presence of optically defined touch sites did not detrimentally affect operator performance. It is important to reiterate that the numbers of errors for using all TEDs in Experiment 2 were essentially equivalent as were the number of errors recorded in Experiment 3 when the IR, AR, CA, and CW TEDs were used. The reason for such a similarity of results for Experiment 2 and, with the exception of the CF TED, for Experiment 3, may be that these tasks are not cognitive tasks. They are recognition and simple menu response tasks, respectively. Therefore, if these TEDs are used in applications where responses to system prompts are required, the TEDs examined here might well perform in an equivalent manner. In the case of the CF TED, alignment problems encountered with this device may have contributed to the disproportionately high number of errors.

Table 6 summarizes the performance results by presenting a rank ordering of the TEDs from least (1) to most (5) number of errors and TT. In addition, a summary

rank ordering across all performance measures and experimental conditions is provided. From this table it is clear the IR and CW TEDs, receiving the same rank, were best overall on the basis of operator performance, followed closely by the CA TED. Further, the CF and AR TEDs received, equivalently, the lowest rank.

TABLE 6

Summary of Rank Orderings of TEDs based on Operator Performance Across the Three Experimental Conditions.

		ERRORS				TT				Σ RANKS
		EXPERIMENT				EXPERIMENT				
		1	2	3	Σ	1	2	3	Σ	Σ
	IR	1	3	2	2	4	1	2	3	1.5
	AR	4	4	4	4	3	5	4	4	4.5
TED	CF	5	5	5	5	1	3	5	3	4.5
	CA	2	1	1	1	5	4	3	4	3
	CW	3	2	3	3	2	2	1	1	1.5

Phase III

The only consistent trend in subjective ranking appears to be that the AR TED received the lowest rank and the CW the highest rank across the ratings. For the passenger seat assignment task (Experiment 2), the CW, CF, and CA TEDs were assessed as the most usable and enjoyable, while the IR and AR TEDs were seen as the least usable. Again, subject comments indicated that the AR was insensitive, the IR too sensitive, and the CW most accurate.

Participants rated the CW, CF, and CA TEDs as the most legible. If display noise was a factor, these ratings would again follow the results of Phase I. The CA TED was best based on the composite rating, as an indicator of overall TED utility. In turn, the IR TED had the least utility for the passenger seat assignment task. The AR, CW, and CW TEDs had equivalent median utility.

In comparison to operator performance, it appears that ratings of TED utility did not follow, and are not consistent with, operator performance. That is, where the IR and CW TEDs were best on the basis of operator performance, the IR received the lowest utility rank across the ratings and the CW was ranked as having median (subjective) utility.

Purchase and Preference. As with the measures of optical quality, operator performance, and subjective assessments, the TEDs were differentially ranked in order of purchase and preference within and across the three

experimental conditions. This seems to indicate that operators do not neccessarily make their decisions on the basis of optical quality, performance, or utility alone, but weigh the combined advantages and disadvantages of each TED. In Experiments 2 and 3, the CW TED was ranked as best for both purchase and preference. However, for Experiment 1, the TEDs were essentially equivalently ranked in order of purchase and preference. These results closely follow the summary ranking of the TEDs based on operator performance and indicates that when the subjects were in a role position as a potential purchaser of a TED, their subjective assessments of TED utility more closely represented the interactive performance results. Subject comments closely followed the purchase and preference ranks as well.

General observations. Several problems with the TEDs were experienced during this research and are noted here. First, the CA TED was extremely sensitive to static electricity. That is, when a sufficient static electric charge was generated by subjects and consequently coupled with panel current at the time of touch, device failure occurred. This problem lead to the discarding of many subjects' data because subjects, then familiar with device operation, could not be re-run. Second, the CF TED was prone to drift and misalignment through repeated use. This problem was primarily evidenced during Experiment 3 (menu selection task). Subjects became frustrated when errors were signaled but the correct response location was touched,

thus leading subjects to probe "around" the touch site (square) and resulting in an increase in errors. Third, due to repeated use, a break in one of the cross wires (CW TED) occurred. However, this device was repaired quickly and no further failures were experienced. The most dependable TEDs were the IR and AR TEDs. However, the response time of the AR was extremely slow and caused subjects to become annoyed.

It is important to state that the problems encountered with these TEDs and in this research should not be construed as typical of the classes of TEDs they represent. The problems may be applicable only to the TEDs employed in this study.

Phase IV

Target acquisition performance (PT and RT) and subjective assessments of TED utility were correlated with both display resolution and display noise level values. However, for the most part, correlations differed in direction for the two CRTs and relatively few correlations were seen as consistent and meaningful across the CRTs.

Specifically, consistent positive correlations were found between both horizontal and vertical "summary" signal-to-noise metric values and both time between target presentation and target touch (PTO) and time between target recognition and target touch (RT). Consistent negative correlations were found between display resolution metrics and the subjective rating of Usability.

Increases in display STN levels produced increases in PT and related increases in RT, indicating that as display signal-to-noise level increased, subjects took longer to discriminate target characters from non-target characters and consequently touch the target character. Further, increases in CRT-TED system resolution produced lower ratings of TED usability.

Because of this mixed result in the correlational data, the authors believe that the data are not reliable or consistent in attributing direct causation of performance to any of the physical measures obtained in Phase I.

SUMMARY AND CONCLUSIONS

Display Quality

The application of the four (AR, CF, CA, and CW) TED overlays produced consistent decreases in the resolution capabilities of the CRTs used in this research relative to the IR (baseline) TED. In addition to reducing overall modulation, the TED overlays reduced display luminance nonuniformity and, with the exception of the CW TED, reduced display noise. The CW device actually increased display noise.

In applications where display resolution is of primary concern, the IR TED is obviously of choice because this TED is not an overlay. The next best TED would be the AR followed in turn by the CF, CA, and CW TEDs. Where display noise is of concern, the CA and CF TEDs are of choice.

Operator Performance

Of the five TEDs evaluated, the IR and CW TEDs produced consistently better performance than did the CA, CF, or AR TEDs. Further, the AR and CF TEDs produced consistantly poorer performance than did the other TEDs.

The different results for the experimental conditions may well indicate that the TEDs evaluated in this research are differentially applicable to different types of tasks. However, it must be remembered that the generic tasks employed in this research are limited and exemplify only a

few of the possible applications of TEDs.

Subjective Utility

The only consistent ratings of TED utility derived from this research were from the subjective assessments collected after Experiment 2 of Phase II. For these ratings (Usability, Enjoyment of Use, and Composite Utility), the CA TED was consistently rated better than the other TEDs. However, the CW and IR TEDs produced consistently higher rankings in order of purchase and preference than did the other TEDs. Further, the AR and CF TEDs produced consistently lower ratings, with the CA delineated as having median purchase and preference.

Correlations

Relatively few consistent and meaningful correlations were found between display quality and both user performance and subjective TED utility.

Summary

Based on the overall results, the most recommended TEDs are the IR and CW. While the CW reduces image quality measurably, its reliability and ease of use rate quite high. Cost-performance tradeoffs are also favorable to the CW compared to the other TEDs used in these experiments.

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